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Physical Modelling in Geotechnics

Centrifuge modelling of silty-sand slopes under intermittent rainfall conditions

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ABSTRACT: Rainfall data from several past landslides show that the slopes barely experience continuous rainfall before the failure. Instead, they can be mostly attributed to intermittent rainfalls. To investigate the impact of intermittent rainfall on slope failure, the present study conducted a set of centrifuge model tests using a mist spray nozzles rainfall simulator. The model slopes made of silty sand were exposed to continuous (Test A) and intermittent rainfall (Test B) conditions. The displacement and the porewater pressure variation of the slopes were measured using an image recording system and porewater pressure transducers, respectively. Two slopes experienced the same rainfall intensity but different cumulative rainfall in total before both the slopes exhibited a similar kind of failure in the same time interval. The porewater pressure development of Test B showed a quick and abrupt behaviour ahead of the failure initiated. The vertical displacement and horizontal displacement of slope in Test A showed a larger value compared to Test B. However, the results of the deformation analysis of Test B showed that continuous displacement has generated permanent deformations in soil slope and a spike in velocity at the end of the second rainfall event has accelerated failure.

Keywords: centrifuge model test, slope, intermittent rainfall, deformation

1 INTRODUCTION

Rainfall-induced landslides are occurring quite frequently all over the world, causing irrevocable damages to society and the economy. Slopes become more vulnerable to fluctuating rainfall conditions originated consequential to climate change. Rainfall infiltration contributes to the development of positive pore water pressure (PWP), loss of matric suction in unsaturated soil and saturation dependent shear strength reduction. These failure mechanisms and associate decrease of the stability level of slopes followed by rainfall infiltration have been studied using tools such as field testing (Askarinejad et al., 2018), large/small-scale physical modelling (Wang and Sassa, 2001), and centrifuge model testing (Take et al., 2004). As a result of replicating the stress levels and repeatability of tests, centrifuge model tests are used to test many hypotheses and cases in relation to rainfall-induced slope failures.

Many reported cases show that landslides have not only occurred at the time of continuous rainfall but also intermittent rainfall conditions (Yang et al., 2017; Dang et al., 2018). However, the significance of intermittent rainfall (continuous wetting and drying) on unsaturated slope behaviour has not been discussed many times in the physical modelling arena. Therefore, the objective of this paper is to carry out a set of centrifuge model tests to examine and highlight the slope behaviour under intermittent rainfall conditions.

2 EXPERIMENTAL SET-UP

2.1 Centrifuge testing

Disaster Prevention Research Institute (DPRI) 24g-tonne geotechnical centrifuge at the Kyoto University was used for testing the slope models. The arm length in flight is 2.5 m. For this study, rainfall was simulated using 18 air atomizing nozzles which use pressurized water flow and air flow (Xu et al., 2021). The rainfall intensity values were calibrated by adjusting the water pressure and air pressure before the tests. In this regard, a tray having 30×30 mm square cups was used. Water was used as the pore fluid and the water tank was fixed to the rigid box. The rigid box (model container) has internal dimensions of 600×300×140 mm (Fig 1). A drainage box is fixed to the bottom side of the rigid box to collect the surface runoff. The scaling factors relevant to the study are given in Table 1.

2.2 Slope material

A type of silty sand soil (Masado soil), which is commonly used in geotechnical applications in Japan, was used in these experiments. According to the particle size distribution carried out, the soil can be categorized as well-graded sand with silt, and the silt content is around 10%. A few trial tests were carried out previously to adopt 1.5 g/cm^3 as the dry density of soil. Under this dry density, laboratory tests were performed to find the saturated coefficient of permeability and soil-water characteristic curve (SWCC). SWCC parameters were determined by van Genuchten (1980) model. Table 2 presents the properties of Masado soil.

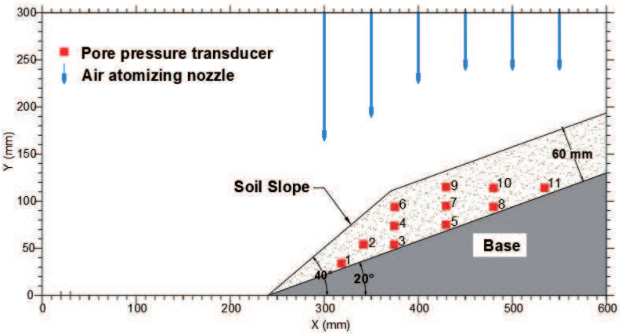

Fig. 1. Schematic diagram of centrifuge model set-up

Table 1. Scaling factors relevant to the study.

Parameter	Dimension	Model	Prototype
Stress	M/LT^2	1	1
Length	L	1/N	1
Time (diffusion)	T_{diff}	1/N^2	1
Rainfall intensity	L/T_{diff}	N	1
Suction	M/LT^2	1	1
Hydraulic Conductivity	L/T_{diff}	N	1

Table 2. Basic properties of slope material used in tests.

Parameter	Value
D_{60}, D_{30}, D_{10} (mm)	0.83, 0.32, 0.15
Particle density (G_s) (g/cm^3)	2.6
Max dry density (g/cm^3)	1.76
Optimum moisture content (%)	15.5
Sat. hydraulic conductivity (m/s)	1.02×10^{-5}
SWCC parameters (wetting) α, n, m	0.41, 2.2, 0.55
SWCC parameters (drying) α, n, m	0.12, 2.32, 0.57

2.3 Slope construction

Prior to constructing the slope, the required amount of dry soil was mixed with respective water contents and kept in sealed bags to homogenize for 24 hours. The initial water content of the soil was maintained at around 10%. After the soil was compacted using the wet-tamping method in layers of 20 mm thickness, extra soil was removed to provide the required geometry. Eleven porewater pressure transducers (PPT) were inserted during the construction of the slope. Several markers were placed between soil slope and Perspex window to catch soil deformations using image analysis techniques.

2.4 Test cases

To study how intermittent rainfall can impact the slope behaviour, two tests have been carried out so far. The first test (Test A) was conducted using 25 mm/hr (prototype) continuous rainfall (Fig. 3), and the second test (Test B) was conducted using 25 mm/hr (prototype) intermittent rainfall conditions (Fig. 4). The intermittent rainfall shows two no-rainfall events each lasts for 15 s to represent the discontinuity of a real rainfall condition. After the model reached stable condition at 50-*g*, desired rainfall was applied.

3 RESULTS AND DISCUSSION

3.1 Observation

With the introduction of rainfall, soil erosion took place in both Test A and Test B merely after 10 s. Eroded soil was deposited at the toe of the slope. Owing to the geometry and high rainfall intensity used in these tests, significant runoff was observed during the tests. Remarkably, both the slopes failed in a similar manner (Fig. 2), and irrespective of rainfall patterns applied in the tests, the first major failure of both the slopes occurred at the same time intervals. It should be emphasized that cumulative rainfall experienced by Test B is 30 s less than Test A. Table 3 summarizes the key observations and elapsed times of the two test cases.

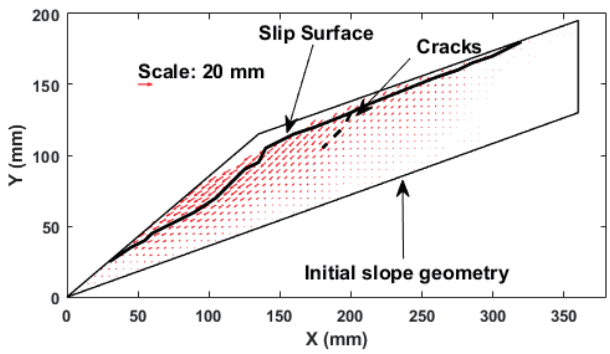

Fig. 2. Rainfall-induced displacement

Table 3. Key observations during the tests.

Event	Test A (s)	Test B (s)
Rainfall starts	0	0
Soil erosion starts	10	10
Showing the signs of continuous deformation	50	90
Major failure	108	110

3.2 Analysis of porewater pressure development

Fig. 3 and Fig. 4 show the time history of the porewater pressure development of PPT 03, 05 and 07 (Fig. 1) of Test A and Test B, respectively. They illustrate that the failures took place while PWP was increasing. According to Fig. 3, the development of positive PWP attributed to the continuous rainfall and progression of the wetting front is clearly shown, whereas Fig. 4 shows positive PWP developed a few seconds before the failure took place. Unfortunately, suction development during spinning-up and loss of suction with infiltration were not caught by the PPT used in these experiments.

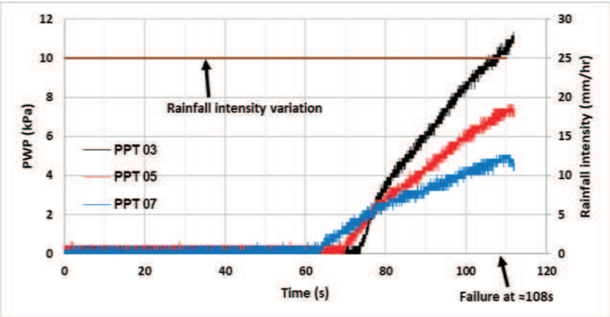

Fig. 3. The evolution of PWP at different locations in Test A

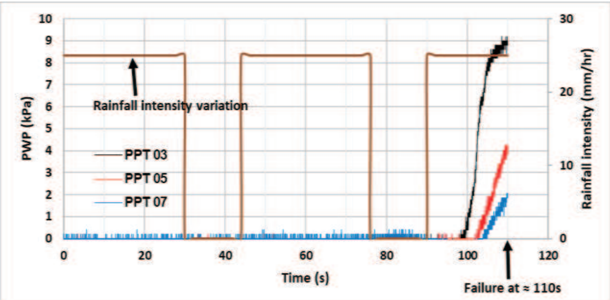

Fig. 4. The evolution of PWP at different locations in Test B

3.3 Analysis of displacement

The progression of landslide along with a comparison between horizontal and vertical displacements of Test A and Test B is shown in Fig. 5. The displacements were measured relative to the toe of the slope. If the movements are leftwards and downwards, the displacement is defined as negative. The horizontal displacement in all the instances shown is larger than the vertical displacement. However, it is worth noting that all the displacements in Test B are rather small compared to displacements in Test A. Further Fig. 5 demonstrates the quick occurrence of substantial localized deformation towards the toe area when the slopes are on the verge of failure.

Point A of the slope, which is slightly rightward to the slip surface, was selected to discuss the time histories of horizontal and vertical displacements during the rainfall. It shows a gradual increment in displacement in both directions with rainfall, but there is a distinct difference in values reached in the two cases throughout the test (Fig. 6a & Fig. 6b). The continuous deformations are inevitable in Test B, especially during 75 s to 90 s, even though rainfall is halted.Considering the similar trends of displacement, the displacement process was investigated with incremental velocities of point A.

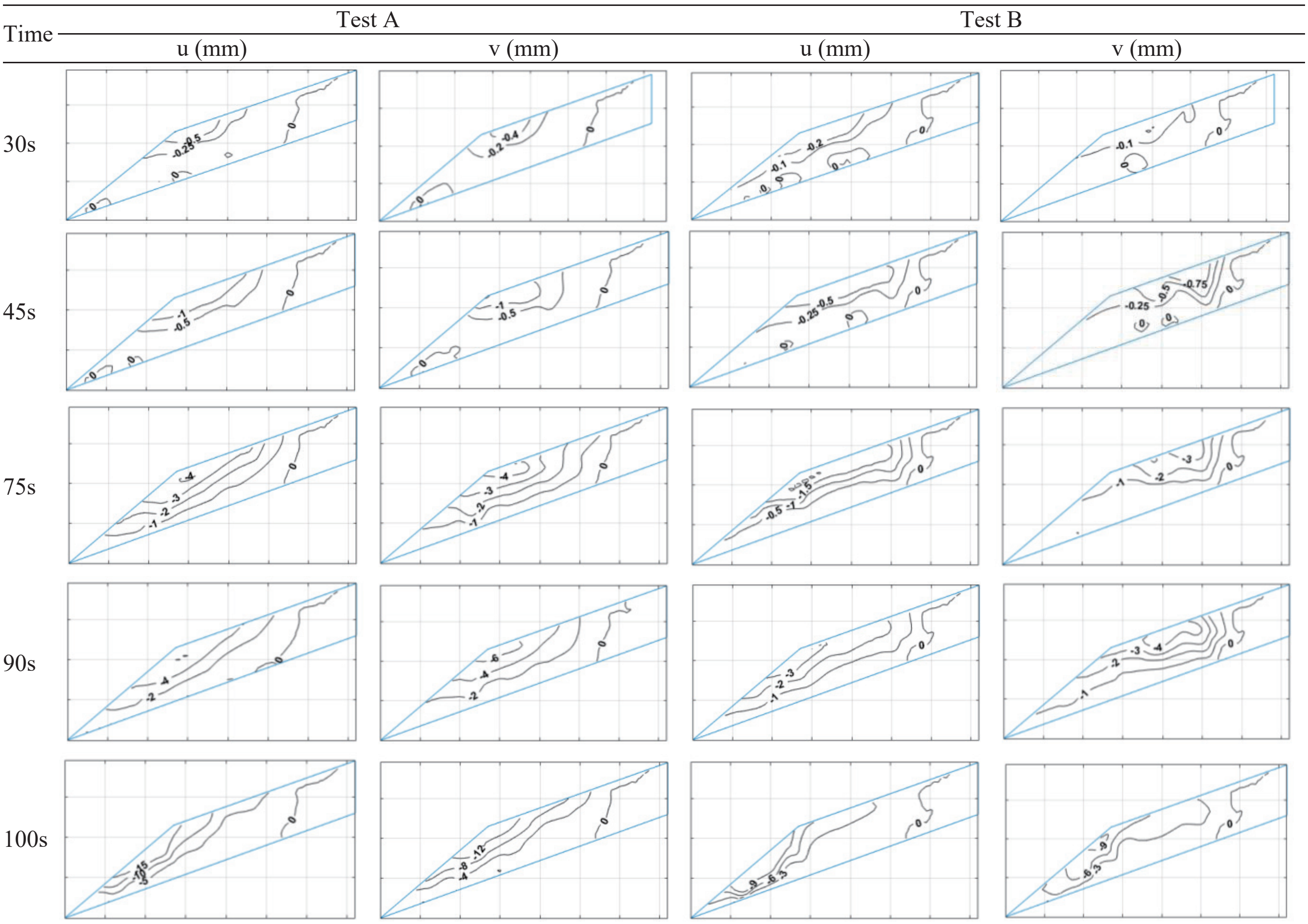

Fig. 5. Contours of displacements of Test A and Test B (u – horizontal, v – vertical)

A close examination of Fig. 6c and Fig. 6d showed that at the end of the second rainfall event (around 70 s) in Test B, incremental velocities increased significantly soon before rainfall stopped at 75 s. Particularly, the horizontal velocity of Test B from 70 s to 75 s reaches up to the level of Test A. Thereafter, since the rainfall is halted for 15 s, velocities show a decreasing trend. Even though the rate of increase of velocity in Test B reduces between 75 s to 90 s, the growth of velocity helped the progression of the landslide as the start of the third rainfall event.

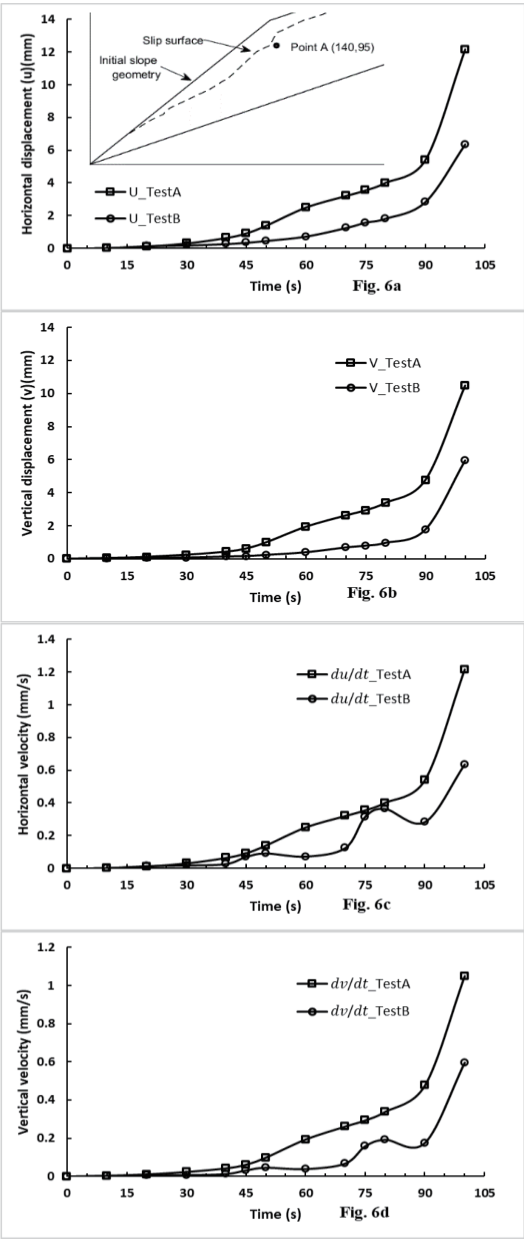

Fig. 6. Horizontal displacement(6a); Vertical displacement (6b); Horizontal velocity (6c); Vertical velocity (6d)

4 CONCLUSIONS

This study used a centrifuge modelling technique to quantify the deformation and PWP development of model soil slope under the effect of intermittent rainfall conditions. The results obtained from the intermittent rainfall conditions are compared with the continuous rainfall condition.

The observed slope behaviour of the two tests shows a similar behaviour with respect to landslide progression. However, the evidence of this study indicates that irrespective of the rainfall patterns and cumulative rainfall experienced by the slopes, both the slopes failed at the same time intervals. The failure that happened in Test A is mainly due to the advancement of the wetting front with infiltration. The rapid increase of PWP ahead of failure of Test B suggests that the effect of intermittent rainfall is quite high and sudden failures are possible in such situations.

The results of the deformation analysis of Test B showed that continuous displacement had generated permanent deformations in soil slope and a spike in velocity at the end of the second rainfall event has accelerated failure. Whilst this study did not confirm the failure mechanism in intermittent rainfall conditions (wetting and drying), it suggested that vulnerable slopes are highly susceptible to failure under intermittent rainfall conditions with low cumulative rainfall. Further more studies are recommended to examine the landslide characteristics with more silty/ cohesive slopes and illustrate the effect of intermittent rainfall conditions.

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